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Towards Affordably Adaptable and Effective Systems

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ABSTRACT

Resilience means different things in different disciplines. From a systems engineering perspective, we define resilience as the ability of a system to adapt affordably and perform effectively across a wide range of operational contexts, where context is defined by mission, environment, threat, and force disposition. A key issue in engineering resilient systems is the lengthy and costly upfront engineering process, which program managers justifiably find unacceptable. This paper presents how advances in computational technology can potentially transform the system development process in new and novel ways to enable fast, efficient, and inexpensive upfront engineering—the key to engineering resilient systems. These processes, in turn, can enable rapid development, deployment, and operation of affordably adaptable and effective systems. © 2012 Wiley Periodicals, Inc. Syst Eng 16: 224–234, 2013

Key words: resilience; engineered resilient systems; adaptability; complex systems; operational contexts; success criteria

1. INTRODUCTION

In an opening statement before the Senate Armed Services Committee in September 2011, Deputy Secretary of Defense Ashton Carter voiced two overriding priorities: how to better serve the deployed troops on their timetable; and how to deliver better buying power to the taxpayers for their defense dollars [Carter, 2011b]. He emphasized that, despite the budget crunch, the country's investments should not be framed as a choice between strong fiscal discipline and strong national defense [Carter, 2011a]. Welby [2011] argues that, in light of these mounting budgetary challenges and the need to make difficult trades in the foreseeable future, one way to make future systems more affordable is to strengthen our commitment to systems engineering fundamentals that are key to the success of defense programs. He emphasized that the looming fiscal challenges offer an unprecedented opportunity to demonstrate the value of systems engineering to DoD.

As systems continue to grow in scale and complexity, several notable trends have been observed that adversely affected the practice of systems engineering [Welby, 2011; US Defense Department, 2012]. To begin with, there has been a reduction in the role and authority of the chief engineer. It is no longer feasible for an individual to fully comprehend and tightly control all the details of design of a complex, electromechanical system. Not surprisingly, this recognition has led to two trends with unfortunate side effects: (a) an increase in specialization among system engineers to address domain-

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specific challenges and knowledge requirements of complex subdomains and (b) an increasing use of integrated product teams (IPTs) to bring these sub-specialties together to assemble complete products. The increasing specialization has resulted in smaller engineering units and introduced barriers to communication among and across design organizations. Concomitantly, the complexity of modern designs has produced a loss of emphasis on core engineering fundamentals. This effect is evident in the poor translation of user requirements into achievable system specifications; inadequate design for manufacturing and test; and fundamental weakness in addressing design factors that drive system reliability and availability. The most critical gap in engineering fundamentals today results from a tendency for design and analysis teams to lose sight of the end product in the midst of fighting technical complexity, and to get overwhelmed by the pursuit of process rather than adequately mapping technical properties into end product features.

Systems engineering has the challenge of addressing these problems, but if conceived as a process-oriented collection of "practices," it is simply not up to the job. For a similar conclusion, see the NAS report on Naval Engineering in the 21st Century [NAS, 2011], which calls for tools with a particular emphasis on early design, arguing that: "There is little research in the United States aimed at developing improved tools and methods for use in the early stages of the design of new naval ships … . Decisions made at the early design stages determine the basic architecture of the ship and ship systems and costs of construction and ownership" [Keane, 2011: 13]. "[T]here are basic research opportunities associated with generic technologies such as systems engineering, multidisciplinary optimization, set-based design, efficiency and accuracy of solvers, physics-based modeling, and multiphysics coupling techniques. These opportunities are particularly relevant for advanced ship concepts where there is often a lack of existing rules-based methods and experimental data and existing tools have not been verified, validated, or accredited for use … . In summary, the health of basic and early applied research relevant to naval ship design tools can only be considered as poor in the United States" [Sullivan, 2011a; Keane, 2011]. These two studies recognized the need for "cultural changes in the approach to requirements, ship design, and ship construction," which are also discussed in more detail by Sullivan [2011b]. Sullivan's paper is representative of advanced thinking about system engineering. Nevertheless, it makes claims with which we agree, and others that we argue are insufficient in defining critical problems facing the field and the direction of solutions. He rightly argues that part of the needed cultural changes include greater collaboration and information sharing among stakeholders. With this, we agree, with some caveats. As Neches [2012] has argued elsewhere, current sequential processes effectively ensure that the right people are not available at the right time for optimal decision-making. There are, however, cost implications if additional stakeholders are simply asked to stand by or are tasked to review a greater number of decisions. Furthermore, the volume of information and proliferation of alternatives is too great to assume that simply making information available will ensure that it is noticed and acted upon. However, Sullivan offers the conventional argument that the required culture change requires acceptance of longer initial development cycles, and deferred production.

Today, analyses are triggered by questions that we decide to ask, rather than by data flows that can detect new information being generated and then automatically propose analyses of implications. There is also relevant research on risk that potentially holds high payoff. Technologies such as real options are being explored as a means to exploit uncertainty and reduce risks [Real Options Group, July 24, 2012; McConnell, 2007; de Neufville and Scholtes, 2011; de Neufville, Scholtes, and Wang, 2006; Copeland and Antikarov, 2003; Page, 2011]. As Koenig [2009] notes, this is a research area that needs to be further developed to yield usable tools. Also, there is interesting ongoing research in exploring near-pareto optimal designs which are robust in the face of requirements changes [Mackenna, 2011]. So, it is safe to say that these important issues are not being ignored. However, while this line of research is necessary, it is not sufficient to overcome challenges associated with uncertainty and risk. This is because the current line of research relies solely on human-initiated activities by humans (i.e., engineers initiate such activities). Unless mechanisms are integrated into an environment that enable the spontaneous generation of analyses based on emergent information, the field of resilience engineering will continue to lack the means to avoid surprise. A second use of risk-management and uncertainty-management techniques entails narrowing candidate human-generated and machine-generated issues to only those that potentially provide the most information and reduce the most risk.

The ratio of engineering work to program cost in DoD has risen from the 10–20% range in the 1950s to a 40–60% range today (E. Kraft, Arnold Engineering and Development Center, USAF AFMC, personal communication). Countering this trend requires a dramatic increase in communications across engineering and acquisition activities. Such communications are vital to understanding problem scope, identifying interdependencies that lead to undesirable outcomes, and making informed tradeoffs and decisions.

Two additional concerns voiced by Welby [2011] are the need to characterize and manage technical risks throughout the product development process and the pressing need to develop new engineering design tools. Existing tools were created for a prior era when processing was cost-prohibitive. This necessitated partitioning designs into feasible subsystems and exploring a limited number of design alternatives in each area. Today, with the advent of computer-aided design (CAD), which has its roots in integrated circuits development, radically new approaches have become possible. Specifically, CAD enables individual designers to manage complexity hierarchically, leverage and reuse components and cell libraries, rapidly and cost-effectively simulate and optimize virtual designs, conduct virtual design validation, and incorporate production planning rules directly into the design process. Welby believes that these principles will eventually find their way into integrated design tools for complex, electromechanical systems in the near future with the advent and maturation of model-based systems engineering (MBSE).

Against the foregoing backdrop, DoD systems are called upon to perform increasingly more complex missions in a variety of operational environments. They need to be rapidly fieldable, affordably adaptable, and effective [Madni, 2011; Neches, 2011]. According to Madni [2012a], these are also the characteristics of *elegant* systems. From a systems engineering perspective, these characteristics collectively define *resilient* systems. In particular, the *affordably adaptable* characteristic implies design for adaptability as well as cost-effective reconfiguration and replacement. The latter is also a key requirement for system of systems (SoSs). From a DoD perspective, the key issues are whether or not a system can be made affordably adaptable and effective; if not, will reconfiguration or replacement achieve these ends? A related issue is whether or not reconfiguration and replacement can be performed better and faster than is possible today. Fortunately, with advances in Model-Based Engineering (MBE), Platform Based Engineering (PBE), and parallel computation, it is becoming possible to design smarter, avoid costly and time-consuming rework cycles, and compress overall cycle times [Welby, 2011]. To achieve this end state begins with understanding how design is accomplished today.

Considerable energy is currently being expended in design. The ratio of engineering work to program cost in DoD has risen from 10–20% in the 1950s to 40–60% today. Consequently, there has been a steady erosion in the time and money that could be spent on purchasing components/subsystems. The continuation of this trend implies loss of economies of scale, reduction in quality, and increased rework. It is not that systems are that much more complicated today; rather, it is that current processes and tools have failed to keep pace with increasingly complex interactions among components and disciplines, as well as with operational demands. As a result, engineering productivity is hampered and less upfront engineering (i.e., engineering in the early phases of the system lifecycle) is being done today. Consequently, problems are being discovered late in the game—making them expensive to fix. Often, the only option is to discard prior work and start over. Meanwhile, the Armed Services (i.e., the customers) have no recourse but to wait. The current approach does not address system affordability or the price of the product, nor does it address the tradeoffs that need to be made to achieve cheaper, better, faster results [Carter, 2011a]. According to Kendall [2011], affordability results from reducing engineering cycles and buying COTS, whenever possible. This paper addresses challenges that need to be overcome and technological advances required to realize the vision of *engineering resilient systems* (ERS). The following section discusses ERS in the context of the acquisition cycle and attempts to clarify the nature of the problem in achieving ERS. Section 2 discusses technology challenges and advances including system representation and modeling, characterizing changing operational environments, cross-domain coupling, trade space analysis, collaborative design and decision support, and success metrics and expected outcomes. Section 3 offers recommendations regarding the key enablers of engineering resilient systems.

1.1. ERS Considerations throughout the System Life Cycle

Looking toward the future, it is becoming increasingly apparent that, for defense systems, engineering design and development processes and tools need to be transformed using promising, new technologies. The transformed processes and attendant tools need to (a) span the system life cycle from concept formation through sustainment and (b) support both rapid fielding activities and traditional acquisitions.

Over the last decade, operational missions have changed from conventional warfare in which multiyear "conception-through-sustainable-deployment" iterations were acceptable, to asymmetric warfare with unpredictable and unprecedented threats. During 2011 alone, we saw an increase in the variety of nonkinetic and kinetic operations, ranging from humanitarian assistance to counterinsurgency to insurgency support, in unexpected locales. In the 21st century, the conception-through-sustainable-deployment cycle times have to be compressed to weeks and months to make a timely impact. As important, with the latest technologies being globally available, it would be a serious miscalculation to make decisions that can potentially compromise the nation's technological superiority. The rate at which adversaries change tactics and improvise threats (e.g., improvised explosive devices) to create tactical surprise strongly reinforces the need to not only sustain but further enhance technological superiority.

Over the years, a variety of terms have been used to characterize robust system behaviors [Beinhocker, 1999; Weick and Sutcliffe, 2007]. Today, that term is "resilience." Resilience has been addressed in a wide variety of contexts ranging from organization [Deevy, 1995; McCann and Lee, 2009; Pat and Pantaleo, 2005; Sheffi, 2005], psychology [Hind, Frost, and Riley, 1996; Holling and Gunderson, 2002], safety-critical systems [Leveson et al., 2005; Jackson, 2009], and ship design [Sullivan, 2011b]. Resilience is a quality attribute like agility or adaptability [Bill, 2002; Christopher and Peck, 2004; Coutu, 2002; Madni, 2008; Hamel and Valikangas, 2011]. While "resilience" means different things in different domains and to different people [Westrum, 2006; Madni and Jackson, 2008; Fiksel, 2003; Fiksel, 2006; Holling, 1996; Malek, 1999; Najjar and Gaudiot, 1999; Amin and Horowitz, 2007; Gunderson and Protchard, 2002; Woods, 2006a, 2006b; Leveson, 2006], *for the purposes of this paper, we define resilience as robustness that is achieved through thoughtful, informed design that makes systems both effective and reliable in a wide range of contexts*. Not only is a resilient system effective in a wide range of situations, it is also readily adaptable to others through reconfiguration or replacement, and displays graceful and detectable degradation of function when pushed outside its operating envelope. The engineering challenge of the 21st century is to infuse this quality of resilience into systems in an affordable, timely manner [Edwards, 2011].

This view of robustness is in sharp contrast to the historical approach to achieving robustness, which has been through overdesign, an unaffordable luxury. At the same time, it is unaffordable to procure systems that meet performance specifications through ad hoc interactions among highly interdependent and tightly coupled subsystems because upgrading/configuring such systems to operate in a new operational environment is not only cost-prohibitive but also unsustainable in the long run. While such designs are occasionally a consequence of inferior engineering, at other times they are the result of lack of anticipation. By now, the systems engineering community has come to realize that it is not possible to satisfy competing demands for better, cheaper, faster by cutting corners. Rather, the system elements and their interactions need to be analyzed in the requisite depth to make informed decisions.

In the world of systems acquisition, time is money. The majority of costs stem from amortizing lengthy development and test cycles over relatively small quantity purchases [Neches, 2011]. And, of course, when engineering issues delay a development program, the "cost meter" continues to run, driving up costs, and potentially reducing the quantity that can be purchased. Eventually, the amount of rework becomes unaffordable, and programs get cancelled. Making it quick and affordable to do upfront engineering will reduce the risk of programs becoming slow and unacceptably expensive.

Affordability depends on: accelerating engineering processes, reducing the time spent on test-and-fix, doing more extensive engineering design and testing faster, doing more in parallel, and using greater computational power to enable more of the preceding activities. Subsequently, decisions about how best to invest the savings can be made (e.g., buy more systems, procure additional systems). To be effective in this regard requires a *dramatic increase in communications across engineering and acquisition activities*. Such communications are vital to understand problem scope, identify interdependencies that lead to undesirable outcomes, and make informed tradeoffs and decisions. To accomplish these objectives, especially when building adaptable systems, it is imperative to understand and explore the range and likelihood of potential situations (characterized by factors such as mission, environment, threat, and Concept of Operations). It is also crucial for generating a range of relevant use cases and test scenarios. While the pursuit of system adaptability is clearly worthwhile, *the testing and evaluation to ensure design success* is just as important if not more. Historically, testing and evaluation address traditional concerns about performance and reliability. As discussed above, risk-oriented and uncertainty-oriented techniques such as real options [de Neufville and Scholtes, 2011; de Neufville, Scholtes, and Wang, 2006; Copeland and Antikarov, 2003; Page, 2011] and/or importance sampling [Wu, 1994] might apply to reducing the cost of such testing and evaluation. An additional, new evaluation issue lies in tradeoff decisions that balance adaptability against performance, reliability, and other measures of effectiveness related to mission success.

Concerns about affordability, effectiveness, and adaptability are inextricably intertwined in Systems Engineering. A resilient system is one that operates within the area defined by an effective balance among these attributes, and that satisfies the needs and circumstances of its customers. As importantly, a resilient system maintains this balance throughout its lifetime.

1.2. Understanding the Nature of the Problem

Neches [2011] argues that a common misconception about engineering resilient systems is that it can entirely be addressed as a process problem, rather than as a science and technology problem. Some systems engineers believe that "if only" current processes were rigorously followed, the problem would take care of itself. Others would rather reengineer using well-known techniques [Hammer and Champy, 1993; Hammer, 1996; Davenport, 1992, 1995]. It is worth recalling that, from the days of Robert McNamara through the Packard Commission and beyond, engineering and acquisition processes have undergone continual improvement and refinement, coupled with diligent efforts to enforce compliance. The results have been unpromising [Drezner et al., 1993; Christensen, Searle, and Vickery, 1999]. Despite 50 years of ongoing process refinements, engineering and acquisition processes still do not satisfy today's needs (Table I).

Systems engineering studies have repeatedly shown that problems discovered late in the system development lifecycle can be up to 100 times more time-consuming and expensive to fix [Neches, 2011; Madni, 1994]. Furthermore, the less upfront engineering is done, the more likely it is that the program will fail. Even so, for program managers to invest in the necessary upfront engineering, it is imperative to significantly reduce the cycle time and cost of upfront engineering. In the absence of necessary upfront engineering, the only recourse is process reforms that are wholly dependent on front-loading program costs to be executed effectively. In today's environment, this approach is hardly viable. Fifty years of combating the misperception that upfront engineering is nothing more than an expensive impediment should have taught the systems engineering community an important lesson: Upfront engineering needs to be much cheaper and faster than it is today. In fact, upfront engineering should serve as a "forcing function" to accelerate problem solution, not merely a means to discover design flaws and defects faster.

To understand the relevant science and technology issues, it is important to get past the common misconception that systems engineering is merely about adhering to arcane processes and working from handbooks of standard practices. By unfairly characterizing the systems engineering discipline as one that tells us what we can and cannot do, the real contributions of the field are unfortunately overlooked. Systems engineering is about identifying interactions among and across component elements of the phenomena of interest, understanding consequences of those interactions, and exploring ways to effectively manage them.

This forward-looking perspective, however, raises certain fundamental concerns. How does one describe and analyze devices, the environment, and the behavioral elements that

Table I. Problems Inherent in Today's Processes

- Fifty years of process reforms have not succeeded in:
  - controlling costs
  - adhering to schedules
  - satisfying performance requirements
- The key reasons are:
  - prematurely culling alternatives
  - making decisions without adequate information
  - engaging in processes that are sequential and slow
  - losing information at every step
  - continuing to perform requirements refinement in an ad hoc fashion

create the interaction between them? What are the computational mechanisms to rapidly generate and test ideas? Given that even these mechanisms are not going to overcome the computational complexity associated with exhaustive analysis and testing, what are the techniques for assessing uncertainty and risk that can help maximize the payoff of investment in engineering work, minimize the likelihood of having to do extraneous work (i.e., work that we choose not to pay for), and help us decide how much to invest? These are some of the deep problems that make ERS a true science and technology challenge. Developing an understanding of these issues is a prerequisite to developing effective solutions that can offer a sustainable competitive advantage.

2. TECHNOLOGY CHALLENGES AND NEEDED ADVANCES

As we delve into how these fundamental problems and engineering activities relate to each other, it is important to also realize that part of the engineering challenge lies in having to satisfy more constraints than ever before. In the past, systems were designed primarily to be effective; now they also need to be affordable and adaptable, with significantly fewer design-test-build cycles. To rapidly create and field affordable and effective systems, programs must conduct comprehensive systems engineering tradeoff analyses to arrive at desired solutions. Specifically, they need to explore attributes such as adaptability, trust, and affordability in the trade space [Neches, 2011]. These considerations need to be revisited when modifications are made during design, manufacturing, and fielding. As importantly, engineers need more informative requirements than they are supplied with today. Requirements refinement needs better grounding in design feasibility and comprehensive exploration of opportunities. Finally, options need to be more thoroughly explored and kept open longer than they are today [Madni et al., 1985]. Figure 1 illustrates the relationship among these considerations.

New tools are needed to enable design for adaptability, effectiveness, and timeliness. In particular, there is a pressing need for models with the requisite semantics to represent different types of designs and to enable more detailed analysis of designs properties than is possible today [Madni, 2012a]. Also needed are tools that collect stakeholders' inputs and gather empirical information relating needs to human behavior. Truly effective designs come from analyzing what people do (i.e., their behavior), not just what they say they want (i.e., their desires). Fortunately, access to ever-increasing and massive computing power allows deeper consideration of tradeoffs and options. Appropriately used, this capability is an important defense against both tactical and technological surprise.

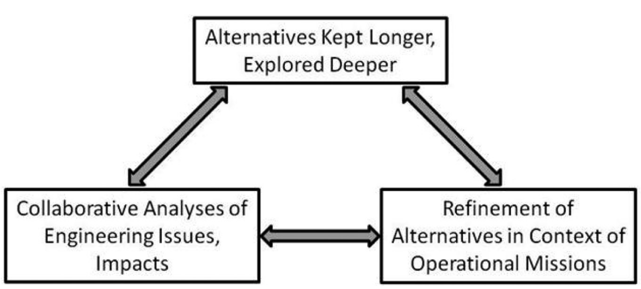

Figure 1. Key considerations in framing an alternative engineering approach.

Model-Based Engineering (MBE) and Platform-Based Engineering (PBE) are useful starting points for developing new engineering tools and environments [Madni, 2012a; Zarboutis and Wright, 2006]. They enable the exploration of design alternatives and adaptability choices by offering computational means to evaluate intra-system characteristics and exploration of system interactions with the external environment. The challenges lie in formulating the specifics. The following paragraphs present the key challenge areas that matter most along with needed technological advances.

2.1. System Representation and Modeling

Although models have taken center stage in systems engineering with the advent of MBE approaches, models should not be equated with systems engineering. In reality, models are an enabler of systems engineering in that they allow representation of multiple types and perspectives needed to capture the physical and logical structures, system behaviors, interactions (with the environment), and interoperability with other systems or systems of systems.

Upon closer examination of the different kinds of models required, and the different disciplines, aspects, and phenomena they need to address, it becomes quickly apparent that there is a pressing need to create and manage multiple classes (executable, depictional, statistical, etc.) and multiple types (device and environmental physics, comms, sensors, effectors, software, systems, etc.) of models. Taking combinatorics into account, this means that there are dozens of different models that need to be developed and made interoperable. Their form and content, and the rate at which they can be created and validated, underlie the gaps which need to be filled. These gaps can be addressed with the creation of: models and simulations combining live and virtual elements; the acquisition and cross-integration of physics-based versus statistical models; the building and integrating critical multidisciplinary, multiscale physics models; automated and semiautomated techniques for acquiring models; and techniques and tools for building adaptable models.

2.2. Characterizing Changing Operational Environments

A critical challenge today is how best to complement the aforementioned models with models of the dynamic operational environment that are needed to drive the behavior of systems [Di Marzo et al., 2007]. This means moving away from "point requirements" and toward acquiring a deeper understanding of customer needs. This shift, in turn, requires directly gathering and modeling operational data, and experimenting with alternative designs against that backdrop to understand the operational impacts of various alternatives.

Today, design and test are conducted to satisfy requirements, such as attaining performance parameters that are hypothesized as being of value under certain conditions. However, this approach fails to recognize what complexity theory and practical experience have shown us—that optimizing in this fashion invariably leads to brittle systems. This brittleness results from the fact that while such solutions may achieve high performance under certain conditions, they do not fully and adequately address the *range* of conditions likely to be encountered. To design and test for resilience across a broad range of conditions requires understanding at a much finer-grained level of how the systems will be used (their Concept of Operations, or ConOps), the environments and threats they can be expected to encounter, and the operational context in which they will be used.

TARDEC GVSET News [Williams, 2011] recently noted that DoD has spent a decade trying to get ground vehicles to be more fuel efficient while preserving their existing functionality. TARDEC recently built a set of Fuel Efficient Ground Vehicle Demonstrators to illustrate these points. In addition, there are instances of vehicle designs created to satisfy unrealistic requirements. For example, a Humvee today accepts an increase in weight and gives up fuel efficiency, in part, to meet a requirement of carrying four 6 ft. 5 in. tall soldiers. An analysis conducted by a TARDEC contractor showed that the statistical likelihood of four men of this height being in the same unit is extremely low. Furthermore, previous fuel economy tests were conducted with these vehicles driving a fixed circuit over a fixed terrain. While these conditions were representative of many driving conditions, the tests conducted did not take into account the frequency with which military missions encountered those conditions. Thus, not surprisingly, these vehicles performed well on the tests but disappointed in actual use. This discrepancy has also been encountered by those who bought automobiles for their EPA ratings, which similarly do not reflect the realities of actual vehicle usage. When TARDEC's contractors collected and statistically modeled data on actual driving conditions in the theater, they were able to design vehicles that performed significantly better both on the old tests and in operational settings.

These simple examples convey the value proposition of real world data collection, analysis, and exploitation on vehicle design. Real world data collection also offers some exciting opportunities and challenges when it comes to the operational environment. For example, today both our social computing systems and our physical systems and environments are being increasingly instrumented to collect real world data for a variety of purposes ranging from marketing to maintenance. Consequently, there are opportunities to leverage such instrumentations and data collection facilities rather than having to build them from scratch. In addition to exploiting instrumented systems and environments, a range of technologies such as synthetic environments are increasingly being used to collect data, present scenarios for practice, and project future conditions for training and mission planning purposes. Leveraging these advances for engineering, beyond making greater use of data already being collected, can result in faster payback and delivery of interoperable systems to potential users (i.e., planners, operators, trainers) of engineering models of physical devices. In addition, test data utilization to refine computational models is another underexploited area in that test data currently collected is not used for this purpose [Madni, 2011; Woods, 2006b].

In light of the foregoing, the specific gaps that need to be filled when it comes to characterizing changing operational environments are: *instrumentation* to collect data from live and virtual operational environments, systems, and system tests; *synthetic environments* for experimentation and learning; *automated and human-in-the-loop acquisition* of operational context models (missions, environments, threats, tactics, and ConOps); *abstraction/generalization* of tests and use cases from operational data; and *synthesis & application* of behavioral/environmental models.

Holland [US Army Corps of Engineers, personal communication, 2011] noted that "ensuring adaptability and effectiveness requires evaluating and storing results *from many, many scenarios* (including those presently considered unlikely) *for consideration earlier* in the acquisition process." A decade from now, the combination of synthetic environments and surrogate models will make it possible for the first time to assess complex weapons systems' Mission Effectiveness Breadth in relevant military contexts. And it all has to start with characterizing changing operational environments and using the resultant models to "drive" system behavior.

2.3. Cross-Domain Coupling

It is important to realize that many of the models described in the foregoing paragraphs already exist. However, today there is a growing recognition that these models need to be expanded and made interoperable. In many cases, model interoperability does not exist. The ultimate goal is to have the ability for complex weapons systems to be modeled fully across multiple domains (e.g., materials, fluids, physics, chemistry) as well as across operational environments.

To make this wide range of models and model classes and types work effectively together requires new computing techniques in addition to standards. While standards are clearly part of the solution, they alone are not the solution. Models can differ in type, detail, coverage, representation, data requirements, and many other aspects that need to be included for good reasons. These include efficiency, maintainability, depth of required knowledge, availability of skills, costs, development phase, demand, and market structures and forces.

From the foregoing, it should be apparent that enabling productivity of people engaged in composing models of systems from heterogeneous components presents challenges that go beyond adhering to standards. Two of the most important challenges are achieving superior interchange between incommensurate models, and resolving temporal, multiscale, and multiphysics integration mismatches. In this regard, there are several issues that need to be resolved to enhance the productivity of both individuals and teams working in this specialized area.

Most of these issues can be resolved by: creating libraries whose contents can be reused; bringing models together rapidly and correctly; accelerating the definition of the workflow between the models; and automating conversion between specific models. The research that needs to be conducted to achieve the foregoing include the creation of:

on-demand composition of modeling and analysis workflows; consistency maintenance across hybrid models through data abstraction, and spatiotemporal data exchange; efficient interoperation through automatic generation of summaries and surrogate models; creation and repair of mappings between modeling systems using semantic features; and interface extensions programming to provide automated boundary condition assignment (parameterization), coordinated cross-phenomena simulations, connections to decision support, and coupling and connections to virtual worlds.

2.4. Trade Space Analysis

Thus far, we have discussed the core capabilities needed for faster and more sophisticated analysis and testing than is possible today. However, fully realizing this transformation requires extending the ability to identify and understand problems, in order to more rapidly and effectively develop solutions. Doing so requires the ability to generate a much larger set of alternatives than is done today and to understand the implications of choosing one over the others. The required capabilities and tools described up to this point certainly enhance our ability to do so. But more can be done, given the growing ubiquity and speed of computing today. Computing advances create opportunities for generating a large number of options [Madni et al., 1985], exploring them in greater detail, and keeping them open longer, while assuring that complexity can be managed. Computing advances also enable the creation of greater computational testing capabilities.

Part of the challenge lies in enhancing productivity by providing tools and "drivers" for efficiently generating and evaluating alternative designs. To this end, there is a need to automate the exploration of a large number of conditions, generate and test more alternative solutions, analyze the resulting data, and deliver the findings on engineering issues and solution tradeoffs to decision makers in timely fashion. As important, evaluating available options in multidimensional trade spaces is a critical issue. Thus, another key challenge is that of control; i.e., we need to help engineers target these drivers effectively because despite advances in computing, computational power is still inadequate to explore every possibility.

In light of the foregoing, the gaps that exist today can be filled with the creation of: guided automated searches, and selective search algorithms; ubiquitous computing for generating/evaluating options; identification of high-impact variables and their likely interactions; new sensitivity localization algorithms; algorithms for measuring adaptability; risk-benefit and cost-benefit analyses tools; integration of reliability and cost into acquisition decisions; and cost-sensitive and time-sensitive uncertainty management via experimental design and activity planning. The massive trade spaces that are invariably associated with complex systems [Kichkaylo and Roesler, 2010] make these issues critical and addressing these gaps a vital imperative.

2.5. Collaborative Design and Decision Support

Ultimately, all technological challenges involve or lead back to people [Neches, 2012; Madni, 2010, 2011]. The people challenge encompasses both providing information to and acquiring information from people. From a technological perspective, advances are needed in collaboration technology, information summarization and abstraction, multimedia presentation, and human computer interaction.

For reasons provided earlier (under Characterizing Changing Operational Environments), information needs to be acquired from a much wider range of stakeholders than is done today. It is tragic, for example, that service members returning from deployments routinely complain about their equipment but without knowing who can resolve their problems. For example, the length of time, from when soldiers first start throwing sandbags into the bottom of their vehicles to when engineers first discover an underbelly blast problem and begin offering effective alternatives to soldiers, needs to compressed. Also, much more complex information needs to be conveyed to decision makers than is done today. This requirement results from the fact that decision makers today are offered opinion-driven and anecdote-driven discussions as the inputs to critical decisions over a limited set of alternatives. In contrast, engineering of resilient systems entails making empirical, data-driven decisions concerning a much richer set of critical alternatives. In so doing, non-engineers must be aided in making realistic assessments of engineering feasibility of various options and opportunities.

The foregoing discussion is not meant to imply that every individual will be communicating with every other individual about everything, all the time. Rather, a key challenge is creating an environment which supports context-driven, targeted information exchanges.

The key gaps that exist today in collaborative design and decision support can be filled with the creation of: usable multidimensional trade spaces; rationale capture; tradeoff prioritization aids; explainable decisions; assessable engineering, system acquisition, physics-based and behavioral models; access controls; and information push-pull without flooding, i.e., saturating the cognitive capacity of humans [Madni, 2010, 2011].

2.6. Success Metrics and Expected Outcomes

The metrics that characterize the engineering of resilient systems span both the product and process perspectives with

Table II. Success Metrics

- Design Adaptability (robustness metric)
  - accessibility and modifiability of diverse system models
  - reuse and replacement potential (modularity)
  - interoperability potential (standardized interfaces, compatible semantics)
  - continuous analyzability (performance, vulnerabilities, trust)
- Engineering Iteration Scope, Rate, and Efficiency
  - ability to integrate 3D geometry, electronics, software in virtual design
  - problem discovery point (how early?)
  - cycle times of risk reduction phases with prototypes (how short?)
  - design/build/test cycle times (how fast?)
- Information Timelines for Decision Making
  - depth and numerosity of options generated
  - breadth of trade space analyses (ConOps, environment)
  - depth of collaboration scope (interaction, iteration)
  - ability to simulate and experiment in synthetic operational environments

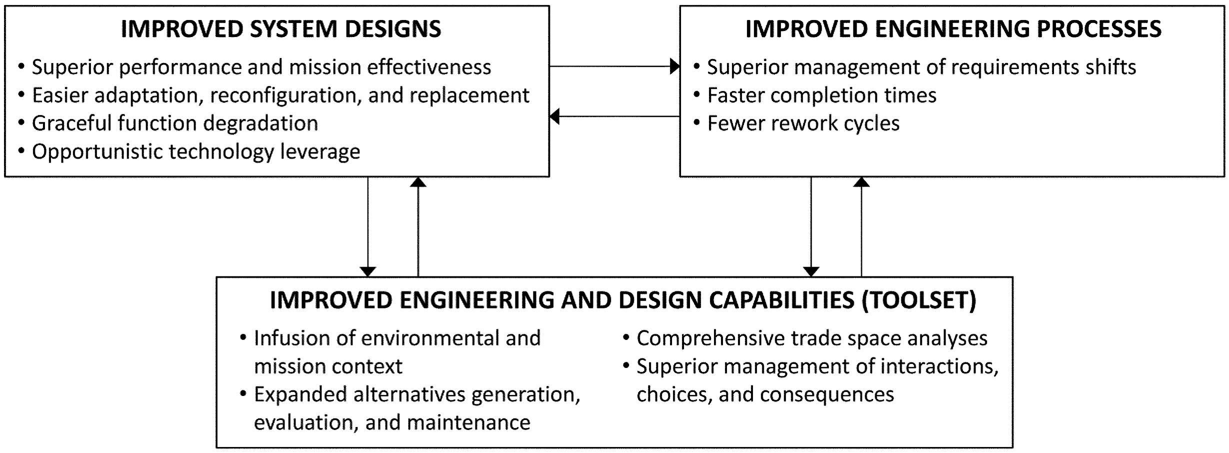

Figure 2. Envisioned end state in ERS methodology comprises three desired outcomes.

advances enabled by technology. The key metrics pertain to the scope and types of design adaptability, the speed and efficiency of engineering iterations, and the ability to inform decisions of mission needs in timely fashion. Table II presents detailed measures associated with these metrics.

The envisioned end state of the ERS methodology comprises three desired outcomes: improved (more resilient) system design; improved engineering processes; and improved engineering and design capabilities (i.e., tools). Figure 2 presents the envisioned end state associated with the proposed ERS methodology. As shown in Figure 2, the expected overall outcome is a technology-enabled methodology for engineering of resilient systems. This methodology can be implemented and evaluated through a series of pilots geared to each challenge area.

3. CONCLUSIONS

This paper has presented a manifesto on engineering resilient systems (ERS) and conveyed potential of technology-enabled innovations in processes and tools for developing affordably adaptable and effective systems. In addition, this paper has sought to clarify the problem by characterizing it as a science and technology problem, rather than a process adherence or reengineering problem. The hard problem from a customer's perspective is defining what customers really need, not what they say they want. Trade space analysis, a key emphasis area, should not be characterized as a search for optimal design; rather, it should focus on the proper formulation of needs. It is important to realize that, when needs are prematurely translated into requirements or key performance parameters, both the process and the product of engineering suffers the consequence. We risk cost and schedule on unvalidated assumptions of technology feasibility while simultaneously limiting ourselves from considering the range of technology-enabled opportunities.

Effectiveness, a key aspect of a resilient system, implies better, informed decision making. A key aspect of effectiveness is the frequency and quality of interaction (i.e., communication) between the different aspects of a process. Today, *design* begins long after *requirements specification*. Instead, the two need to be performed much closer together and be in tight communication with each other.

In the future, we will need rapid, easy, inexpensive upfront engineering to secure program managers' buy-in for decisions made with engineering rigor. We have emphasized that upfront engineering will need to: automatically consider multiple variations; propagate changes, and maintain constraints; introduce and evaluate multiple usage scenarios; explore technology and operational tradeoffs; iteratively refine requirements; adapt and build in adaptability; and learn and update. We have also emphasized the importance of creating rapid new ways to develop and field affordable, effective systems. Accomplishing this objective entails: deep analysis of tradeoff to optimize the solution with adaptability, effectiveness, and affordability requirements sufficiently considered in the trade space; audit trail maintenance when modifications occur during design, manufacturing, and fielding; frequent transmissions of information requirements to the engineer; requirements refinement grounded in design feasibility and opportunities; and consideration of multiple alternatives in suitable depth while ensuring that they are kept open as long as feasible.

Performing the aforementioned activities quickly, repeatedly, and adaptably requires new technologies. These new technologies are identified as: models with representational richness to express and analyze more designs than previously possible; learning about operational context to inform both design and test; and uncertainty-based and risk-based tools to manage combinatorics of deeper systems engineering analyses of tradeoffs and options. And, finally, enhancements to Model Based Engineering (MBE) and Platform Based Engineering (PBE) methods, when combined with greater computational power, are important enablers of trade space exploration, and reduction in rework, cycle times, and costs—the key enablers of engineering resilient systems.

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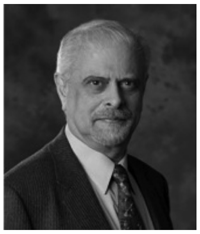

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